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Project X Energy Station Workshop Report

Report by the Organizers and Co-Conveners of the Project X Energy Station Workshop

David Asner (PNNL)
Patrick Hurh (FNAL)

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Yoursy Gohar (ANL)
Mary Peterson (PNNL)
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Dave Wootan (PNNL)

March 2013

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

On January 29–30, 2013, Fermilab hosted a workshop with the objective to identify and explore the nuclear energy relevant research and development that would be possible in a Nuclear Energy Station associated with the Project X Linear Accelerator (linac). Recognizing that the U.S. Nuclear Energy mission will always require the use of test reactors, the hypotheses that a Nuclear Energy Station associated with Project X could accelerate and enhance the ability to test and evaluate new materials and advanced reactor fuels was explored. Forty-five of the invited participants including staff from the U.S. Department of Energy (DOE), DOE Laboratories, universities, and other institutes attended the workshop. These participants were invited based on their technical expertise and relevant experience.

The first stage of Project X could provide approximately 1 MW of beam dedicated to a spallation neutron source for nuclear materials and fuels research (energy station), or shared with a physics mission facility based around similar neutron source requirements. The consensus among the participants was that the highest priority opportunities were associated with fusion and nuclear energy mission needs for irradiation of fusion and fast reactor structural materials. The Project X Energy Station would have to provide a fusion and fast reactor relevant neutron flux at a minimum of 20 dpa per calendar year in a reasonable irradiation volume. In addition, the Energy Station could enable the in-situ real-time measurements of various separate-effects phenomena in fuels or materials, which would be very valuable to the modeling and simulation technical community. Such capabilities are more feasible in an accelerator-based system than a reactor. The final mission need identified for the Energy Station was the integral effects testing of fast reactor fuels, including driver fuel, minor actinide burning fuel, and transmutation of spent fuel.

Key findings include:

- A MW class spallation source for either the energy station or particle physics missions would generate quantities of radionuclides and will require significant infrastructure and capabilities that Fermilab currently does not possess. This will also require an update of the laboratory's Environmental Impact Statement. The irradiation of fuel materials will not drive any additional requirements in the small quantities that were discussed. These hurdles were not judged insurmountable, but will require significant effort and attention.
- The issue of thermal stability of test materials was identified as needing further investigation to quantify the requirements and enable comparison with historic beam trip data. Given the reliability and typical maintenance periods for modern superconducting linacs, expected beam interruptions will have an impact on thermal stability and potentially affect microstructure evolution of test materials.
- The advantages and disadvantages of liquid and solid targets were discussed extensively, but it was agreed that either technology could be made to work. A preferred choice will depend on final design requirements.
- There was a general consensus that combining the particle physics mission with the nuclear energy mission in a single target station would be preferred over separate stations competing for the proton current available from the stage-1 linac. Sharing neutrons would be better than sharing protons at the stage 1, 1 MW beam power.

Specific actions to further evolve the concept of an Energy Station were identified and include the following:

- Develop conceptual target designs that serve both particle physics and nuclear energy missions
- Develop a testing program plan for the Energy Station that capitalizes on the unique characteristics of a high-intensity accelerator and spallation source
- Define/refine the technical requirements to support the proposed testing program plan
- Compile relevant Project X Energy Station (PXES) design parameters to support the high-priority mission needs and provide them to the beam and target designers
- Investigate the beam on/off issues for both short and long time scales. This will likely take the form of a literature review to determine which transients have the potential to be problematic due to thermal and radiation damage effects
- Further consideration must be given to desired damage rate/sample volume specifications to provide a meaningful irradiation capability
- Neutronics modeling of the notional Project X Energy Station concept needs to be refined to evaluate beam options (e.g., dual or rastered beam) to optimize flux and flux gradients in maximum usable test volumes.

Acronyms and Abbreviations

ADS	accelerator-driven subcritical systems
ANL	Argonne National Laboratory
ATR	Advanced Test Reactor
CW	continuous wave
DOE	U.S. Department of Energy
DOE-NE	U.S. Department of Energy Office of Nuclear Energy
EIS	Environmental Impact Statement
ESS	European Spallation Source
FES	Office of Fusion Energy Sciences
FFMF	Fission Fusion Materials Facility
FNAL	Fermi National Accelerator Laboratory
INL	Idaho National Laboratory
ISIS TS1	ISIS Target Station 1
JAEA	Japan Atomic Energy Agency
J-PARC	Japan Proton Accelerator Research Complex
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science Center
LBE	liquid lead bismuth
LBNE	Long Baseline Neutrino Experiment
linac	Project X Linear Accelerator
MEGAPIE	Megawatt Pilot Experiment
MTS	Materials Test Station
ORNL	Oak Ridge National Laboratory
PIE	post-irradiation examination
PNNL	Pacific Northwest National Laboratory
PSI	Paul Scherrer Institute
PXES	Project X Energy Station
R&D	research and development
SINQ	Swiss Spallation Neutron Source
SNS	Spallation Neutron Source
TEF-T	Transmutation Experimental Facility-ADS Target Test Facility
UK	United Kingdom
WG1	Working Group 1
WG2	Working Group 2

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1.0 Introduction

Fermilab is developing a design of a High Intensity Proton Linac, known as Project X, to support future High Energy Physics Programs. Fermilab's accelerator research and development (R&D) program is focused on the superconducting radio-frequency technologies for the proposed Project X. Pacific Northwest National Laboratory (PNNL) and Argonne National Laboratory (ANL), two U.S. Department of Energy (DOE) National Laboratories with experience in Nuclear Energy, are supporting Fermilab by focusing on developing and evaluating the concept of a high-intensity continuous wave proton beam target station for nuclear energy applications. PNNL developed a report on the Project X Energy Station (Wootan and Asner 2012) that explored the potential opportunities and this report was the impetus for this workshop. The objective of the workshop was to identify and explore the nuclear energy relevant R&D that would be possible in a Nuclear Energy Station associated with the Project X Linear Accelerator (linac) and identify the design requirements for conducting the research. Previous workshops have focused on the nuclear and particle physics research associated with Project X.

The goal of this workshop was to bring together U.S. researchers working in areas as diverse as:

- accelerator-based applications;
- nuclear and material science;
- applications of high-intensity proton beams and targets;
- advanced nuclear reactor concepts, advanced nuclear fuel cycles, light-water reactor sustainability, and enhanced and accident tolerant fuels; and
- isotope production.

The U.S. Nuclear Energy mission will always require the use of test reactors, but one of the hypotheses is whether a Nuclear Energy Station associated with Project X could accelerate and enhance the ability to test and evaluate early research concepts. The workshop participates were asked to identified the synergy and benefit that the Project X linac could bring to the nuclear energy community.

The workshop was organized by PNNL and Fermilab in collaboration with ANL. The workshop agenda began with overall sessions focused on Nuclear Energy research and development plans, role of accelerators in nuclear energy, material science programs and facilities, future needs for irradiation testing, and Project X Scientific Plans. The forty-five participants then organized into two working groups—one focused on the Energy Station Proton Beam and Target Design Requirements and the second one focused on the Science and Technology Applications. This workshop report summarizes the key topics and conclusions from the working groups and recommends future considerations. This workshop report will be utilized by Fermi National Accelerator Laboratory (FNAL) and others for considering the nuclear energy mission opportunities for Project X and for pursuing additional technical studies to quantify the design requirements and research programs.

2.0 Project X Energy Station Program Opportunities

The Project X Energy Station program opportunities provided below were derived from the workshop discussions and from the PNNL-issued whitepaper (Wootan and Asner 2012). The opportunities are summarized for the missions associated with nuclear energy, physics, and fusion energy. One of the major opportunities is associated with irradiation of materials, so research activities using ion irradiation in lieu of neutron irradiation were included in the workshop discussions.

2.1 Nuclear Energy

The Office of Nuclear Energy (DOE-NE) has a diverse set of R&D responsibilities, including the development of advanced fuels and materials, advanced instrumentation for safeguards, separations technologies, and systems analysis. The DOE's Nuclear Energy R&D Roadmap, as laid out in an April 2010 report to Congress, identifies four main objectives around which DOE-NE's R&D activities are organized:

- Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors;
- Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals;
- Develop sustainable nuclear fuel cycles; and
- Understand and minimize the risks of nuclear proliferation and terrorism.

Facilities to support this R&D are key to DOE-NE's success, particularly in the area of neutron irradiation testing. Neutron irradiation facilities with stable, well-characterized test volumes and capable of testing fuels and materials from coupon size up to assembly size in a neutron environment characteristic of thermal or fast spectrum nuclear reactors are needed to conduct a robust nuclear energy R&D program. High-level considerations for the suitability of neutron irradiation facilities include the neutron flux spectrum, the fuel pin cooling environment, flexibility in the types of fuels that may be tested, and the use of advanced instrumentation that can measure temperatures and other important parameters.

The tremendous advance in accelerator capabilities brought about through several key technology developments in the last 10–15 years can be harnessed to address the nuclear energy R&D objectives identified above. These advances have been articulated in two recent reports issued by DOE's Office of Science, *Accelerators for America's Future* (DOE 2010) and *Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production* (Abderrahim et al. 2010).

With respect to nuclear energy, recent advances in accelerator technology make viable the realization of accelerator-driven subcritical systems (ADS) for waste transmutation and energy production. Active R&D programs focused on ADS research exist in many countries around the world, with the United States being a notable exception since it ceased funding such research in 2004.

Materials irradiation is another clear and compelling application of accelerators to nuclear energy R&D. The option currently favored by the fusion materials community is the International Fusion

Materials Irradiation Facility, which proposes to accelerate 250 mA of deuterons to 40 MeV and use the d-Li stripping reaction to produce an intense neutron flux with irradiation characteristics similar to that to which fusion reactor first walls are subjected. Another viable option involves intense medium-energy (~1 GeV) proton beams driving spallation neutron sources to reproduce the intense radiation environment of fusion reactors. The first stage of Project X could provide the beam energy and power needed to drive such an irradiation facility.

Current nuclear fuel R&D activities include transuranic-bearing metallic and ceramic fuels taken to high burn up in Idaho National Laboratory's (INL) Advanced Test Reactor (ATR), high-temperature gas reactor TRISO fuels, and reduced enrichment dispersion fuels for research reactors. Development of new fuels is traditionally a highly-empirical, lengthy, and expensive process. The desired approach is goal-oriented and science-based, where fundamental experiments are tightly coupled with theory and multi-physics modeling and simulation at multi-scales for a fundamental understanding of fuels and materials behavior under irradiation. The goal is faster and cheaper delivery of advanced fuels and materials for commercial deployment making maximum use of the available infrastructure and limited R&D resources. Small-scale, phenomenological tests (in contrast with integral prototype testing during the development phase) with data collection at multiple length and time scales (4 decades) are needed to validate the modeling and simulation tools currently under development. National infrastructure must support a range of needs from integral testing to validation at the microstructural level.

Because major nuclear infrastructure is limited, new facilities should be treated as a community asset and adopt a National User Facility model. DOE-NE, responsible for significant nuclear infrastructure at INL, will look first to INL for capability placement. Placing facilities at other locations requires differentiation in capability and/or cost. The community currently does not have a good process to prioritize proposed non-INL facilities.

2.2 Physics

Previous workshops on Project X were focused on the nuclear and particle physics science opportunities. It was important for this workshop, focused on nuclear energy applications, that the participants gain an understanding of the scientific interest by the physics community in Project X. More details can be found in the report from the "Project X Forum on Spallation Sources for Particle Physics, March 19–20, 2012."

The experimental program enabled by the full scope of Project X builds on current investments in the U.S. Intensity Frontier experimental program including the Long Baseline Neutrino Experiment (LBNE), the Fermilab muon campus, Fermilab short-baseline neutrino experiments, and electric dipole moment experiments. It offers opportunities to extend these programs with new initiatives to achieve a comprehensive exploration of these fundamental questions: Are there new forces of nature, new properties of matter, or new dimensions? Project X will be a unique facility for the exploration of Intensity Frontier phenomena. The combination of multi-MW beam power available at a variety of energies, beam formats tailored to the needs of individual experiments, and recent advances in detector technologies will enable a suite of experiments unrivaled in the world.

Stage 1 of Project X enables scientific opportunities through the following experimental probes: neutrinos, muons, and kaons. Additionally, Project X Stage 1 will provide up to approximately 1 MW of beam power to a new suite of ultra-cold neutron and various electric dipole moment experiments driven by a spallation target facility optimized for particle physics. There is potential for substantial broader impacts beyond particle physics, including irradiation resources for materials important for advanced nuclear fuel cycle research and fusion research, and the capability to drive a muon spin rotation materials research program.

2.3 Fusion Energy

Fusion reactor materials radiation effects R&D needs were presented that described several materials irradiation conditions that are unique to fusion systems in general and magnetic fusion systems in particular. These include high dose, significant He production, and interaction with hydrogen isotopes over a wide range of temperatures. For near-term fusion applications, structural materials will need to survive 40–80 dpa at 350–550°C. For longer-term fusion applications, exposures will be 150–200 dpa at 300–1000°C. Achieving high dose and prototypic He generation rates are particular requirements for fusion materials development. Irradiation in existing facilities cannot produce prototypic effects and extrapolating to fusion-relevant conditions is not feasible. To significantly advance the state-of-the-art in fusion structural materials, a high flux source of high energy neutrons is required. The fusion materials community has recognized this need for at least 30 years, and over that time they have evaluated numerous reactor, accelerator, and plasma-based sources of high-energy neutrons. A neutron spallation source like the notional Project X Energy Station offers ample neutron flux at fusion-relevant energies in a large irradiation volume, along with high levels of He and H production. A continuous wave accelerator driving a spallation source might address one of the major concerns with the accelerator neutron source approach; namely, the microstructural consequences of pulsed irradiation available in existing spallation sources. The Office of Fusion Energy Sciences (FES) is preparing input to support the Office of Science in formulating a 10-year prioritization of scientific user facilities. One of the facilities already identified as a need for FES is a neutron source to more accurately simulate fusion-relevant conditions. It was suggested that the workshop participants consider contributing a white paper to support this effort describing the notional Project X Energy Station as a candidate facility to meet this need. A white paper was submitted to FES after this workshop (Asner 2013).

2.4 Neutron versus Ion Irradiation

The “Emulation of Neutron Irradiated Microstructures with Ion Irradiation” was presented during the workshop with ion irradiation studies being conducted in lieu of neutron irradiations to address the time required to reach high dose in neutron irradiations. Proton irradiation can produce up to 1 dpa/day, and heavier ions can produce up to 100 dpa/day. However, it was acknowledged that one of the drawbacks of ions relative to neutrons is reduced mean free path, resulting in localized irradiation damage regions. For example, 3.2 MeV protons in structural steels will penetrate about 40 µm, and 5 MeV Ni^{2+} ions will penetrate less than 2 µm. This makes ion irradiation most suitable for fundamental studies of radiation damage, particularly with regard to microstructural evolution, irradiation-assisted stress corrosion cracking, and swelling. In order to use ion irradiation to simulate neutron irradiation damage, it is necessary to ensure that comparable microstructures are produced. This typically requires conducting ion irradiations at higher temperatures than neutron irradiations. Benchmarking the ion irradiation results to neutron irradiation results (e.g., dislocation loop size/distribution, radiation-induced precipitates, radiation-induced segregation) is important to ensure that the proper temperature offset is selected. The micro-mechanical techniques that are currently being developed may help bridge the gap between microstructural changes and material properties.

3.0 Project X Energy Station Concept and Comparison

3.1 Energy Station Notional Energy Station Concept

The Project X Energy Station notional concept described in this section is not based on the description prepared for the workshop, and is not the result of the workshop. The intent of the workshop organizers was to use the workshop discussions to inform and provide suggestions for further development of the Project X Energy Station towards a conceptual design. Figure 1 shows a cross-sectional schematic depiction of the initial notional concept of how the Project X Energy Station could be configured. More details can be found in the presentation materials https://indico.fnal.gov/conferenceTimeTable.py?confId=5836#20130129.detailed (select the presenter for each day to access the presentation) and in the PNNL whitepaper (Wootan and Asner 2012). The proton beam from the Project X accelerator is extracted at a beam energy of 1 GeV and a beam current of 1 mA, for a total beam power of 1 MW. This beam is directed on a spallation target to produce neutrons. For these initial studies, the proton beam is assumed to be spread uniformly over the target diameter, because the exact mechanism of spreading the beam (such as rastering or defocusing) has not been determined.

The proton beam is directed on a heavy metal liquid spallation target, creating fairly large volumes of neutron flux that rival or surpass the limited test volumes available in existing test reactors. The initial concept for the spallation target is a 10-cm diameter flowing liquid lead bismuth (LBE) target that produces approximately 30 neutrons per proton. The 1 GeV protons penetrate approximately 50 cm into the LBE target. The melting point of LBE is ~126°C, so a 200°C inlet temperature, 300°C outlet temperature, and maximum of 2 m/s flow velocity (based on erosion and corrosion concerns) appear reasonable. The optimum target diameter is one that provides adequate heat removal while maximizing the neutron flux. Smaller diameters produce higher neutron flux levels close to the target, but the beam power is deposited over a smaller volume. For example, reducing the target diameter from 10 cm to 5 cm increases the peak neutron flux from 0.6E15 to 1E15 n/cm^2/sec. A similar LBE spallation target technology was demonstrated in the Megawatt Pilot Experiment (MEGAPIE) in 2006 (Wagner et al. 2008). The neutrons produced in the spallation reaction have an energy spectrum similar to a fission spectrum, but with a high energy tail extending to the beam energy. Use of a solid spallation target, such as tungsten, has also been considered, and results in a higher peak flux but shorter axial extent. This accelerator beam and spallation target arrangement could be developed in either a vertical or a horizontal layout. A horizontal layout is shown in Figure 1, which offers benefits for the accelerator design, because it would eliminate the need for a 90-degree bend in the beam.

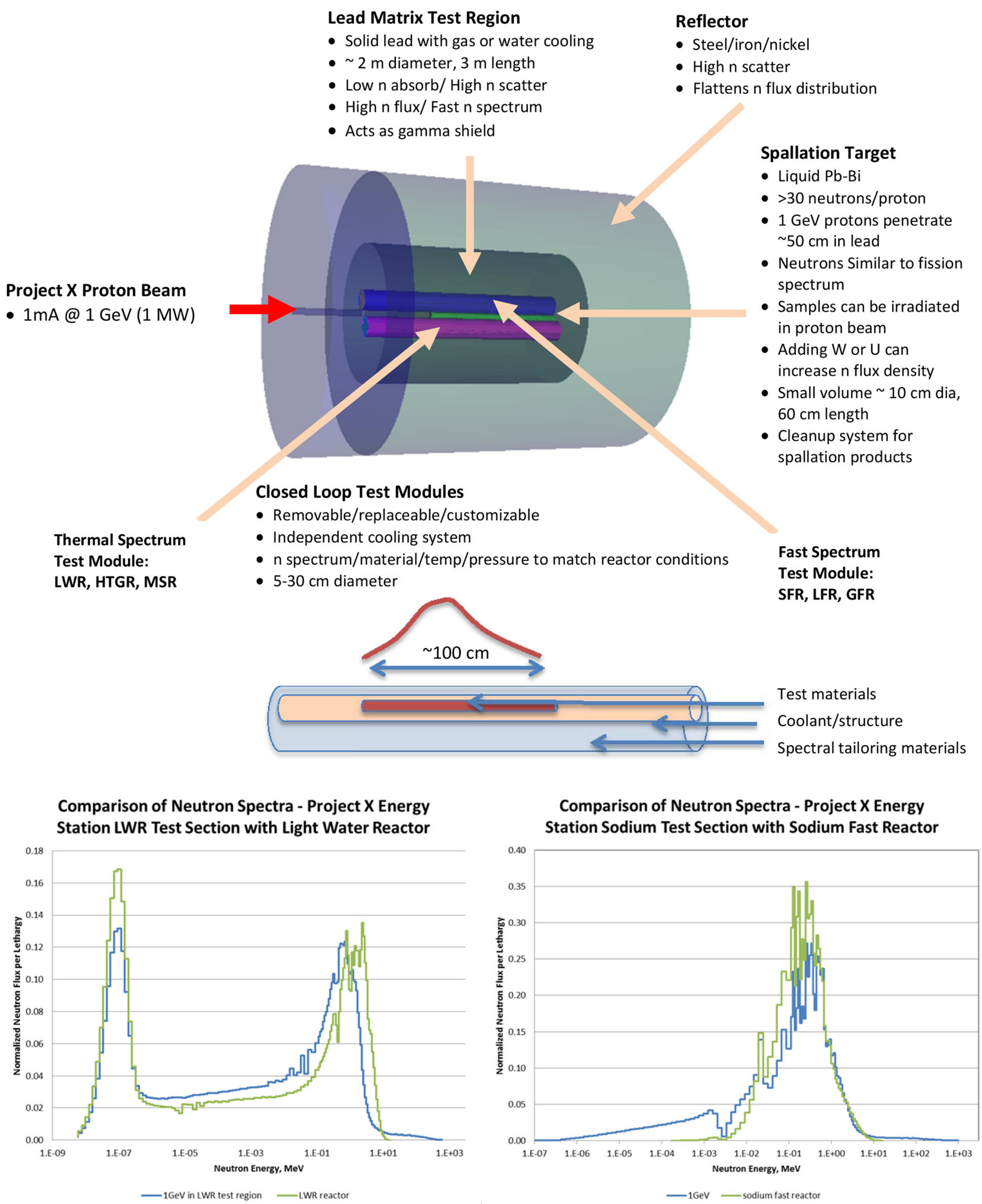

Figure 1. Energy Station Concept

The spallation target is surrounded by a high-scatter, low-absorption test matrix that reduces the radial leakage of neutrons from the system. A solid lead matrix 200 cm in diameter and 300 cm long, with the surface of the spallation target recessed 100 cm from the front matrix surface was used in the reference case. The heat deposited in the matrix can be removed by air or gas coolant channels, or water around the periphery. This matrix has holes to provide space for test loops and other fixed irradiation spaces. The distribution of neutron flux in the test matrix is shown in Figure 2. Volumes at various flux levels are shown in Table 1. The region with a neutron flux greater than 1E14 n/cm^2/s extends axially over 100 cm, allowing long samples to be irradiated. Peak dpa rates in iron range up to 20 dpa/year. Other materials considered for the test matrix included Zircalloy, which has better strength at high temperatures compared to lead, but is not as effective at scattering, resulting in lower neutron flux levels.

The various closed-loop test modules are arranged in the test matrix around the spallation target. The number of test modules can be varied depending on demand. The energy station could start with one module, and then additional modules could be added as needed. The native neutron spectrum in the target matrix is similar to that in a lead fast reactor, so little modification of the spectrum would be needed to test that environment. Modules for testing other fast reactor environments, such as sodium fast reactors or gas fast reactors, would require minimal tailoring of the neutron spectrum. Thermal reactor environments, such as pressurized water reactors, boiling water reactors, graphite reactors, or molten salt reactors could be reproduced in a module of less than 30-cm diameter. Modules can be tailored for a variety of environments, such as fusion reactor materials testing, isotope production, or cold neutrons for physics tests. The size of these modules will depend on the amount of room required to reproduce specific reactor operating conditions of temperatures, pressures, materials, and neutron spectrum. The optimum distance of the module from the spallation source depends on the combination of neutron spectrum, dpa rates, and He and H generation rates desired. These modules could be arranged in a vertical or horizontal arrangement around a horizontal beam spallation target. Multiple test modules are envisioned, each with an independent test region and coolant loop. Each test module can be removed and reinstalled independently of the others. These reconstitutable assemblies can provide tremendous flexibility in designing tests that meet client needs, which will evolve over time. Extensive instrumentation and temperature control are also key attributes that can be used to provide a testing environment tailored to particular program needs. Effects of any differences in neutron spectra between those simulated by flux tailoring in the Energy Station modules and the individual reactor concepts can be evaluated through comparable materials irradiations and interpretation of the results. Closed-loop modules have been utilized in test reactors such as the Fast Flux Test Facility (sodium), BOR-60 (sodium, lead), and ATR (pressurized water).

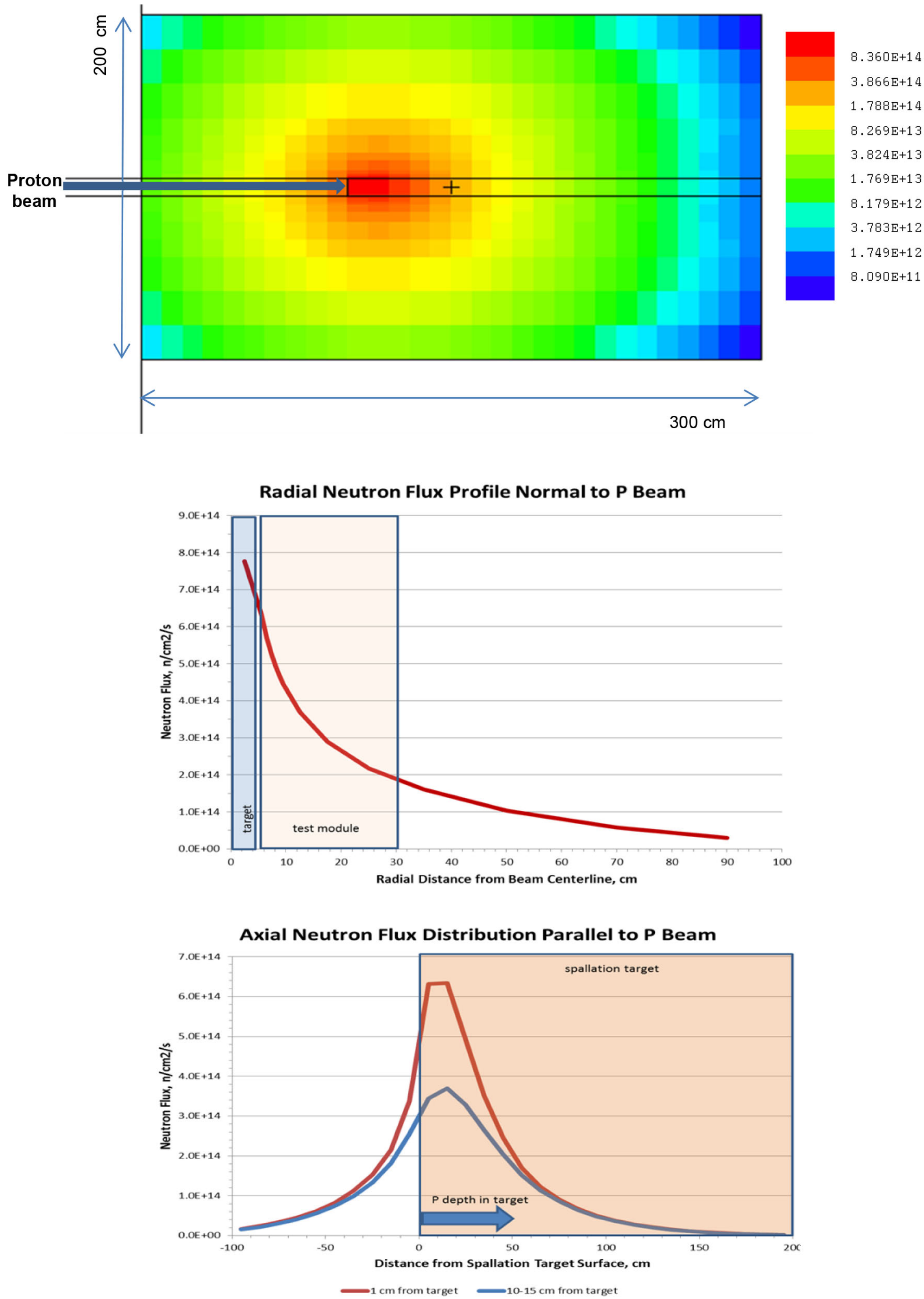

Figure 2. Neutron Flux Distribution in Lead Matrix Test Regions

Table 1. Neutron Flux Volumes in Lead Matrix Test Region

Neutron Flux Range (n/cm2/s)	Axial Extent (cm)	Outer Extent (cm)	Volume (liters)
>5e14	30	8	~2.8
>3e14	50	15	~23
>1e14	110	60	~600
>5e13	160	80	~2000
>1e13	250	100	~9000

3.2 Summary of Existing and Planned Spallation Neutron Source Facilities

Several presentations were made during the workshop that compared existing and planned spallation neutron source facilities. Table 2 compares the Project X Energy Station concept with existing proton spallation accelerator neutron source facilities. The proposed Energy Station accelerator beam parameters used the current studies are a continuous wave proton beam of 1 MW beam power, 1 mA beam current, and 1 Gev beam energy. As described in this workshop, the latest parameters for the 1 GeV Project X beam are 0.91 MW beam power, 1 mA beam current, and 1 GeV beam energy. The Project X Stage 1 beam timing for the 1 GeV beam incorporates a 60 msec beam-off period every 1.2 seconds, resulting in a 95% duty factor for the otherwise continuous wave (CW) beam. This CW beam produces a high neutron flux and the high duty factor provides a neutron irradiation capability to accumulate fluence comparable to large research reactors, but with the volume and flexibility to tailor the neutron spectrum, temperature, coolant, and structural materials to match a wide variety of both thermal and fast spectrum reactor types. Except for the Swiss Spallation Neutron Source (SINQ) cyclotron accelerator, the existing neutron spallation facilities are pulsed systems. They are all designed for producing neutron beams, such as for scattering studies, and not necessarily for materials irradiation. The Los Alamos Neutron Science Center (LANSCE) and Spallation Neutron Source (SNS) facilities are comparable in power to the proposed Energy Station, but have pulse frequencies of 20 or 60 Hz, lower duty factors, and are not designed with the flexibility for tailored irradiation testing that is envisioned for the Project X-driven Energy Station.

Table 2. Comparison of the Energy Station with Existing Spallation Sources (Source: http://pasi.org.uk/Target_WP1)

	Project X Energy Station	**LANSCE Lujan – LANL[(a)]**	**SNS – ORNL[(b)]**	**SINQ MEGAPIE – PSI[(c)]**	**SINQ Solid Target – PSI[(d)]**	**ISIS TS1 –UK[(e)]**
Initial Operation	~2021	1972	2006	2006	1996	1984
Target	LBE	W	Hg	LBE	Pb/Zr	W
Beam Current, mA	1 (0.91)	1.25	1.4	1.25	2.3	0.2
Beam Energy, GeV	1	0.8	1	0.59	0.59	0.8
Beam Power, MW	1 (0.91)	1	1.4	0.8	1.2	0.16
Beam Frequency, Hz	CW, 40 MHz	20	60	CW	CW	50
Pulse Length, μs		0.25	0.7			0.1
Duty Factor, %	>50		6			2.5
Neutron Flux, n/cm^2/s (vol, liters)	6e14 peak >3e14 (23L) >1e14 (600L)	beam	beam	beam	beam	beam

(a) Los Alamos Neutron Science Center–Lujan – Los Alamos National Laboratory
(b) Spallation Neutron Source – Oak Ridge National Laboratory
(c) Swiss Spallation Neutron Source, Megawatt Pilot Experiment – Paul Scherrer Institute
(d) Swiss Spallation Neutron Source, Solid Target – Paul Scherrer Institute
(e) ISIS Target Station 1 – United Kingdom

Table 3 compares the Project X Energy Station concept with proposed or planned proton spallation accelerator neutron source facilities. All of the other planned neutron spallation facilities are pulsed systems, except for perhaps the Indian ADS system, compared to the continuous wave Energy Station beam. The Japan Proton Accelerator Research Complex (J-PARC) and Indian systems are planned to be oriented to ADS R&D and would have subcritical fuel regions surrounding the spallation target. The SNS second target station and the European Spallation Source (ESS) are planned to be mainly neutron beam facilities, but could be used for limited materials irradiation. The Materials Test Station (MTS) and SNS facilities are comparable in power to the proposed Energy Station, but have pulse frequencies of 120 or 20 Hz, respectively, and lower duty factors compared to the continuous wave Project X Stage 1 1 MW beam. The MTS dual target design is the result of optimizing for the mission of sodium fast reactor advanced fuel pin rodlet irradiation testing with specific requirements for peak flux and spatial gradients. This drove to the MTS specific target and pin irradiation space configuration. This MTS configuration did not include any tailoring of the neutron spectrum to specific reactor types, and the primary irradiation volume was limited to the space between the two tungsten spallation targets. The SNS second target station is proposed to be a neutron beam facility that is not focused on a neutron irradiation testing mission.

Table 3. Comparison of Energy Station with Proposed/Planned Spallation Sources (Source: http://pasi.org.uk/Target_WP1)

	Project X Energy Station	MTS/FFMF[(a)] – LANL	SNS Long Pulse – ORNL	J-PARC TEF-T[(b)] – JAEA[(c)]	ESS - Sweden	ADS – India
Initial Operation	~2021	Not Scheduled	?	?	~2018	?
Target	LBE	W (dual) LBE cooled	W/Ta or Hg	LBE	W He cooled	Pb, LBE, W
Beam Current, mA	1 (0.91)	1.25	1.15	0.4	50	10-30
Beam Energy, GeV	1	0.8	1.3	0.6	2.5	1
Beam Power, MW	1 (0.91)	1	1.5	0.2	5	10-30
Beam Frequency, Hz	CW, 40 MHz	120	20	25-50	14	CW
Pulse Length, μs		1000	1000	500	2860	
Duty Factor, %	>50	7.5		1.25	5	
Neutron Flux, n/cm^2/s (vol, liters)	6e14 peak >3e14 (23L) >1e14 (600L)	1.6e15 (0.2 L) 40 fuel rodlets; 0.45 L materials	beam	ADS	2.2e15(0.4L) target 1.2e15 (5L) reflector	ADS

(a) Fission Fusion Materials Facility
(b) Transmutation Experimental Facility-ADS Target Test Facility
(c) Japan Atomic Energy Agency

4.0 Working Group 1 Summary Report: Energy Station Proton Beam and Target Design

Working Group 1 (WG1), convened by Patrick Hurh (FNAL), Bernie Riemer (ORNL), and Michaele (Mikey) Brady Raap (PNNL), was charged with developing the conceptual design requirements for the proton beam and target facility for the Energy Station. This involved assessing the science requirements coming from Working Group 2 (WG2) and the combined sessions, evaluating the beam and facility design options (including possible target technologies), exploring radiological implications of the Energy Station located at Fermilab, and discussing near future work required to advance the Energy Station concept.

4.1 Science Requirements

Working Group 1 assessed the Energy Station science requirements to be at a very early, pre-conceptual stage. Requirements are not currently listed in a single document and rarely quantified. Still, several goals and critical areas for development were identified and discussed.

- Neutronic Performance Requirements

  Science goals were identified as maximizing the neutron flux/fluence with the desired energy spectrum to match or surpass that available in test reactors as well as maximizing the available test volume with acceptable flux/fluence parameters. One promising solution was presented in the PNNL white paper (Wootan and Asner 2012). However, this analysis used simplified geometry and beam parameters that likely over-estimate the yield for both goals compared to an actual target facility design incorporating realistic structural and safety components/systems and beam parameters. Discussion pointed to other concepts that deliver the beam in such a way to maximize high flux/fluence test volumes while perhaps providing sufficient neutrons to feed particle physics experiments as well (such as the LANL MTS proposal).

Working Group 2 worked to better define the neutronic performance requirements by identifying a narrower, but unique to the Energy Station, scope of research (see Section 5.1). WG1 recommends that these requirements be refined and quantified to enable conceptual design activities to progress.

- <u>Irradiation Sample Environment Requirements</u>

  Irradiation sample environment discussions focused on thermal stability requirements. Although no quantifiable requirements were identified, the goal of a continuous irradiation at a stable temperature is desired. Concerns were raised about expected and unexpected beam off periods as thermal cycling can affect microstructure evolution in the samples and obscure test results. In addition, periods of beam off with samples remaining at irradiation temperature can result in annealing of damage likewise interfering with proper interpretation of results. Recent historic beam trip data was presented by Dr. Kevin Jones (ORNL) for the SNS accelerator complex. The data showed that on average for FY12 beam trips between 1 and 10 seconds in duration occurred 22 times per day. In addition, long-duration trips (greater than 1 hour) occurred once every 3 days. This trip history indicates that active heating/cooling systems will be required to minimize impact on materials science. WG1 recommends further development of quantifiable thermal stability requirements per alloy or fuel type and finding common denominator requirements to compare to historic beam trips.

- <u>Functional Requirements</u>

  A number of functional requirements were discussed, including:

  – Upgradeability – Upgrading the facility in beam power and energy seemed to be a distinct possibility. It is recommended that the maximum upgraded beam parameters be identified so that facility infrastructure that cannot be upgraded later is initially designed for the maximum values (presumably shielding, cooling capacity, and beam aperture/optics).

  – Direct proton irradiation – Irradiating materials using direct proton irradiation was not found to be attractive for nuclear materials needs because of the two orders of magnitude higher gas production to damage ratios (atom parts per million/displacements per atom) typical from high-energy proton irradiation. However, there is some interest from the particle physics community to utilize this target area to test target materials for radiation damage effects. It is recommended that direct proton irradiation of materials be incorporated into the target facility as an ancillary function that does not detract from the nuclear materials and particle physics core missions.

  – Sample material composition – Materials selected for testing may vary widely from structural materials to fissile fuel material. There was not a prototypic list of materials presented. It is recommended that a list of initial candidate test materials be developed to enable assessment of any impact to safety, environmental, or design issues.

  – Compatibility with a target station optimized for particle physics research – It was recognized by both Working Groups that it would be preferable to share the neutrons from one spallation source rather than share the proton beam between two sources. It is recommended that target facility conceptual design efforts focus on a dual-use target station that satisfies both nuclear materials and particle physics mission needs.

- <u>Operational Requirements</u>

  A vision for the operational user paradigm for the Energy Station was not presented. Understanding the typical operating cycle for nuclear materials irradiation testing is necessary to design the target facility and supporting infrastructure. Some of the issues to consider are:

  – Required up-time (availability)

  – Time to change out a test module

  – Re-packaging of samples into new module necessary for high dose test runs

  – Quality assurance of user-designed and/or built test modules and equipment.

  It is recommended that the vision for a typical operational cycle be developed to enable derivation of design requirements.

- <u>Beam/Facility Design Options</u>

  – Project X beam parameters

    Options for Project X beam parameters are relatively limited. Initial parameters are stable at 1 GeV and 900 kW on target. Beam structure is on for 1.2 seconds and off for 60 msec. This structure is not thought to affect thermal stability, but may affect annealing processes and must be looked at more closely. The beam spot size on target is one adjustable parameter that should be optimized for neutronics and target lifetime. The PNNL white paper uses a 10-cm diameter, uniform distribution of protons. Most likely a Gaussian distribution would be more realistic.

  – Target technology options

    The PNNL notional Energy Station concept assumes a 10-cm diameter liquid lead or liquid lead-bismuth target surrounded by a lead matrix 2 m in diameter. This represents a state-of-the-art target concept with some similarities to the MEGAPIE (PSI) experiment and the SNS mercury target. However recent work at SNS and ESS have proposed rotating solid metal targets instead of flowing metal targets as viable design options for megawatt-class spallation sources. WG1 discussed the advantages and disadvantages of each technology. This is shown in Table 4. This listing is not exhaustive, but is a first pass that should be developed further and reviewed. It should be noted that at this early stage, there is not a clear choice of preferred technology for this application.

Table 4. Comparison of Liquid Metal and Solid Metal Targets. Green represents a positive attribute. Red indicates a negative attribute.

Category	Liquid Metal	Solid Metal
Corrosion	Material compatibility issues may require R&D and monitoring`	Target material may need cladding (especially water-cooled tungsten)
Environmental Safety and Health	Hg and Pb both have toxicity issues	Toxicity of water/gas cooling not an issue
		Decay heat may be an issue; loss of coolant accidents need to be addressed
Heat Removal	Easy to remove heat from beam area	Usually have to rotate target or raster beam to keep target temperature within limits
	Liquid metal pumping proven technology	Gas or water cooling proven technology
Operational	LBE must be kept in molten state; otherwise "frozen pipes"	
Radiological	Liquid metal can leak causing contamination problems	Water cooling can leak causing contamination problems
	LBE can create low levels of polonium	Water cooling has tritium and Be-7 issues
	Hg vapor saturation in air is high, creating a contamination control problem	
	LBE freezes at room temperature, potentially making it easier to control contamination	
	Liquid metal can be drained from spent container vessel and re-used	Entire solid target assembly must be disposed at end of life
	Off-gas from liquid systems is a greater issue with liquid targets	
Structural	Container is radiation damage limited	Target material is radiation damage limited

- Radiological Implications

Safety requirements for DOE accelerator facilities are found primarily in DOE O 420.2C, *Safety of Accelerator Facilities*. Chapters II and IV, *Fire Protection* and *Natural Phenomena,* of DOE Order 420.1b, *Facility Safety*, also apply to Project X and the Energy Station. Additional safety requirements that must be addressed are those found in 10CFR835, *Radiation Worker Protection*, and 10CFR851, *Occupational Worker Protection*.

Similar to any accelerator facility with a spallation neutron source, the radiological impacts associated with Project X and the Energy Station that need to be examined include: contamination, radioactive waste, radioactive atmospheric discharges (tritium), radioactive liquid effluents, storage/handling of radioactive material, receipt/packaging/shipping of radioactive material, and residual-radiation from activated materials. These impacts/hazards will need to be reviewed for the primary systems (linac, spallation target, materials for neutron irradiation) and any secondary systems used to facilitate operations either for safety or experiment control (e.g., target heat removal, target maintenance, target drives, cover gas systems, secondary liquid or gaseous effluents). In addition to radiological safety control features, the ultimate disposition of the materials and waste used/generated in the facility should also be key design considerations.

In contrast to the types of materials and hazards typically present in accelerator facilities used primarily for basic physics research, the Energy Station concept introduces the potential to include fissionable materials. The ability to handle fissionable material is necessary to enable research in the investigation of fuel materials either in the development of new fuels or in the transmutation of existing irradiated fuels. Order 420.2c, *Accelerator Safety*, does not preclude the use of fissionable materials (irradiated or unirradiated). In fact, the Order specifically permits equivalency or alternate standards to be used when accelerator facilities "contain, use or produce fissionable materials in amounts sufficient to create the potential for criticality based on the configuration of the materials." The "configuration" of these fissionable materials must be closely controlled such that the potential for criticality remains unchallenged under normal operating conditions and credible upset conditions. Any plans to integrate capabilities to perform destructive analysis of fissionable materials post irradiation should be carefully evaluated to understand the impact/introduction of criticality safety concerns. Material control and accountability concerns/requirements are also introduced with the presence of fissionable materials and special actinides and should be integrated into the Project X scope.

R&D into the accelerator transmutation of waste using irradiated fuel samples introduces the potential for "special actinide materials" to be present. Existing Fermilab operations do not include operation as a "nuclear facility" (Safety & Health Category 1) but do accommodate operations at the Category 2 and Category 3 levels. At the Category 2 and Category 3 levels, there are well-defined threshold amounts of certain actinides that can be present. Above and beyond these defined categories, the current Environmental Impact Statement (EIS) at Fermilab imposes additional limits on fissionable and special actinide materials. One key item to note is that the installation of a spallation target at Fermilab will likely introduce sufficient changes to require an update to the EIS independent of the materials that might be irradiated in an Energy Station (including special actinides).

4.2 Conclusions

In conclusion, Working Group 1 recommends that work continue to identify synergies between particle physics and nuclear materials research towards development of an integrated target facility design. This will require development of a vision for eventual operation of the facility, making possible the identification of infrastructure requirements for a megawatt-class spallation source physics and nuclear materials irradiation user facility. These operational requirements will likely exceed the current knowledge and experience base at Fermilab and must be fully developed and quantified to ensure success of the program.

5.0 Working Group 2 Summary: Science and Technology Applications

Working Group 2, convened by David Senor (PNNL), Yoursy Gohar (ANL), and Eric Pitcher (LANL/ESS) was charged with

- Reviewing existing and proposed accelerator-based nuclear materials science facilities and available test reactors with an eye toward opportunities for exploiting unique, complementary, and niche characteristics of the Project X proton beam.

- Identifying the role(s) that a Project X Energy Station could play to fill the immediate and future needs for the nuclear fission and fusion research communities and define the path forward for identifying and creating a viable user base.
- Evaluating the proposed PNNL conceptual facility design in regards to meeting the identified scientific and technological needs.
- Working with WG1 to understand how a Project X Energy Station scientific program might be bounded by Fermilab site-specific regulatory and internal policy directives.
- Developing, to the extent possible, the target facility scientific requirements for a Project X Energy Station.
- Identifying the knowledge or data gaps that R&D could address in the near term to validate the proposed science program, refine the target facility-scientific requirements, and/or develop the required technologies for a Project X Energy Station.

This involved assessing the requirements coming from the opening and combined sessions and the input coming from WG1.

5.1 Identification of Mission Needs

The primary goal in the limited time available for discussion in WG2 was identification of high-value mission needs that could take advantage of the unique characteristics of the Project X beam to conduct research of interest to DOE-NE. The guiding principles behind identification of the mission needs included the following:

- Does the Project X beam provide unique conditions of interest to the materials and fuels community?
- What niche materials and fuels applications are enabled by the Project X beam conditions?
- What materials and fuels applications are complementary to (not duplicative of) existing reactor- and accelerator-based irradiation facilities (with an emphasis on domestic capabilities)?

After defining the high-value technical needs, it will be relatively straightforward to identify relevant specification goals to provide guidance to energy station designers. A follow-on action to the workshop will be quantification of the relevant design parameters based on the mission needs identified below. The highest priority mission needs relevant to the PXES, in rough order of priority are:

- Fusion reactor structural materials – there is no facility available anywhere in the world that can provide fusion-relevant neutron flux and achieve a minimum of 20 dpa per calendar year in a reasonable irradiation volume.
- Fast reactor structural materials – there are limited numbers of fast reactors internationally, but none in the United States. The value of the PXES for these materials is similar to that for fusion reactor materials. Thermal reactor irradiations with tailored flux can achieve close to the right spectrum, but at relatively low dpa rates. In addition to materials relevant to conventional fast reactor concepts, there are newer fast reactor concepts (e.g., the TerraPower traveling wave reactor) that require ultra-high doses to simulate very long service lifetimes (e.g., 400+ dpa in cladding alloys).

- In-situ, real-time measurements of various separate-effects phenomena in fuels or materials (e.g., microstructural evolution, pellet-clad chemical interactions, fission gas release). Such in-situ measurements are, in principle, more feasible in an accelerator-based system than in a reactor, and they are very valuable for modelers, but sensor technology will require concurrent development. In-situ measurements are relevant for fusion materials and fast reactor fuels and materials, but also could be relevant for thermal reactor fuels and materials because of the difficulty obtaining this sort of information in test reactors. Separate-effects investigations of this type would likely require at least encapsulated fuel pellet samples.
- Integral effects testing of fast reactor fuels, including driver fuel, minor actinide burning fuel, and transmutation of spent fuel. These tests would provide value to the fuels community for many of the same reasons as described above for fast reactor materials. Integral effects tests such as these would likely require rodlet-scale testing.

A possible additional application of the Project X Energy Station is production of unique research isotopes that cannot be obtained without the very high neutron energy spectrum. Examples include Si-32 and Ac-225. It is not envisioned that the Energy Station would be used in a production mode, with the associated schedule, separations, and yield issues, but rather in a mode to facilitate production of research quantities of isotopes on a schedule consistent with normal Project X accelerator operations. There was some discussion that this mission might be more appropriate at later stages of Project X when more beam power is available to share between users. Another possibility is that this mission could be addressed at a different location in the Project X beam via parasitic scattering and absorption, rather than building this feature into the Project X Energy Station.

A variety of other potential materials- and fuels-related areas of study were discussed that did not seem to offer as compelling a case for use of the Project X Energy Station when considered in context of existing reactor- and accelerator-based facilities. Some of the areas discussed in this category included irradiation of thermal reactor materials and fuels (with the one exception described above), neutron- or synchrotron-based materials science, high-energy neutron cross-section measurement, and transient testing. In addition, the question of direct irradiation in the proton beam was considered. In general, the difficulties of relating proton to neutron irradiation, particularly at high neutron energies that cannot be benchmarked by comparison with reactor data, seem to outweigh the potential advantages of reaching high dpa rates by directly using the proton beam for irradiation. Additional difficulties with this approach include very high and non-prototypic He generation rates and H implantation.

There is a range of sample sizes for structural materials of interest, from very small (millimeter-scale) to relatively large (maybe 10 cm). The smaller end of the size range is appropriate for fundamental studies of irradiation damage mechanisms, while the larger end of the range is appropriate for bulk samples needed for engineering property measurements. Thus, the irradiation volume must be designed to accommodate the full range, meaning there must be areas with relatively uniform (and high) flux over centimeter-scale dimensions. At the same time, the irradiation facility should include not only replaceable large modules as described in the notional PXES concept, but also fixed, perhaps smaller, irradiation positions to accommodate limited specimens for long-term irradiations to achieve high dose (200+ dpa).

For both materials and fuels irradiation testing, active temperature control of test specimens during irradiation is an absolute requirement. While relatively straightforward during steady-state operation, the issue of beam trips and downtime (both planned and unplanned) must be addressed. These transients exist on both short time scales (beam trips and downtime during normal operation) and longer time scales (planned and unplanned extended outages). It is possible that some of the events could have consequences for irradiation damage mechanisms (e.g., cascade annealing, atomic diffusion, phase transformations), particularly for samples located in the highest-flux regions adjacent to the proton beam and spallation target. Farther away from the target, it is likely that short time scale events will be smeared out and less consequential. There will likely need to be specifications related to temperature control during off-normal events as extended temperature transients can introduce significant uncertainty in irradiation data interpretation. It was suggested that perhaps SNS or the International Fusion Materials Irradiation Facility offer a potential model for some of the specifications associated with beam trips and down time.

The issue of beam availability is a significant one for materials or fuels irradiation testing. For materials, maximizing the dose rate per calendar year is desirable, while for fuels maximizing the irradiation time per calendar year is desirable. For both, higher availability is desirable. PXES availability of 70% is probably needed to provide the desired dose and fission rates.

There was considerable discussion on the implications of the high-energy tail resulting from spallation. This is an issue that will require further consideration, but there are potentially good as well as bad implications. For fusion materials, the high energy tail offers the potential to achieve a variety of dose and He generation rates, which could significantly enhance the understanding of irradiation damage mechanisms and effects in a regime that has received very little attention (due to lack of fusion-relevant neutron sources with high dose rates). For fission reactor materials, on the other hand, the high-energy tail could be problematic due to non-prototypic high He generation and, possibly, transmutation rates. Ultimately, the impact of the high energy tail for both fusion and fast reactor materials will need to be assessed on an alloy-by-alloy basis.

In general, it appears that the Project X Energy Station will need to accommodate at least rodlet-sized fuel pins, comparable to the capabilities proposed for MTS, to be useful to the fuels community for evaluating fast reactor fuels. There also was consensus that it does not make sense to consider equipping Project X Energy Station to perform post-irradiation examination (PIE) on fuels or materials because existing infrastructure and capabilities are maintained already in the DOE complex at great cost. However, at a minimum, the Project X Energy Station facility will have to have the capability to handle irradiated materials (and potentially fuels) and properly package those samples for shipment to other DOE sites for PIE. This is a non-trivial capability that will need to be considered carefully. In addition, it is highly desirable for the facility to have the capability to receive, as well as ship, irradiated materials and fuels. For example, it would be beneficial to irradiate previously irradiated materials to reduce the time necessary to reach high dose. Similarly, for research on spent fuel transmutation, the facility must be able to receive previously irradiated and properly packaged spent fuel.

Another capability that must exist, either in-house at Fermilab or cooperatively arranged with other DOE labs (e.g., INL, PNNL, ORNL) is experiment and module design expertise. Even if existing capabilities are utilized at the DOE laboratories, FNAL will require safety analysis and design review expertise to evaluate experiment and module designs submitted by users. In addition, FNAL will need to evaluate bounding safety cases for experiment and module design. As an example, FFTF and Experimental Breeder Reactor II both had user's guides that outlined all the requirements that experiments had to meet to be accepted by the reactor facility. FNAL may want to consider development of such a user's guide for the PXES. Finally, it is strongly recommended that FNAL involve safety, security, environment, and quality assurance organizations early in development of the PXES design to identify and resolve issues while they are still manageable.

A recommendation provided by the working group is that the neutron flux and spectrum be benchmarked (e.g., with flux wires or equivalent) soon after the facility becomes operational to facilitate accurate neutronics modeling for subsequent experiments.

6.0 Future Work and Considerations

Working Groups 1 and 2 did not identify any experimental work outside of that generally required of high-intensity target facilities (radiation damage R&D, heat removal R&D, etc.) due to the very pre-conceptual stage of facility development. Instead, future work should concentrate on:

- Develop conceptual target designs that serve both particle physics and nuclear materials.
- Develop a testing program plan for the Energy Station that capitalizes on the unique characteristics of a high-intensity accelerator and spallation source.
- Define/refine the technical requirements to support the proposed testing program plan.

Future work and considerations that were identified by Working Group 2 includes the following:

- Compile relevant Project X Energy Station design parameters to support the high-priority mission needs and provide them to designers as a starting point.
- Further consideration of beam on/off issues for both short and long time scales. This will likely take the form of a literature review to determine which transients have the potential to be problematic due to thermal and radiation damage effects.
- Further consideration must be given to desired damage rate/sample volume specifications to provide a meaningful irradiation capability.
- Neutronics modeling of the notional PXES concept needs to be refined to evaluate beam options (e.g., dual or rastered beam) to optimize flux and flux gradients in maximum usable test volumes.
- An opportunity to vet the technical priority of the proposed PXES mission needs is a review by the DOE-NE Technical Review Panel. This would address a concern raised by Todd Allen related to how the wide variety of concepts proposed under various DOE initiatives never seem to get evaluated or prioritized in the greater context of all other concepts.
- The DOE Office of Fusion Energy Sciences is soliciting input for a white paper on future fusion energy science facilities. This is an opportunity to raise awareness of the possibility and capabilities of the PXES within the fusion materials community. A white paper was prepared and submitted after the workshop (Asner 2013).

7.0 Conclusions

The Project X Energy Station Workshop provided a good forum for bringing together ideas, concerns, and expertise from the accelerator, particle physics, and nuclear energy communities. The participants worked to come to a better understanding of the nuclear materials testing needs and how those needs can be satisfied in a Project X target facility. In particular:

- The Workshop identified unique mission priorities that a Project X Energy Station could provide, namely:
  - Fusion structural materials irradiation
  - Fast reactor structural materials irradiation
  - Fuels development for:
    - Fast reactor integral effects
    - Fuels in-situ separate effects
- A MW-class spallation source for energy station and/or nuclear physics will generate quantities of radionuclides that require significant infrastructure and capabilities that Fermilab does not currently possess and will require update of the Environmental Impact Statement.
- The Workshop identified that thermal stability of test materials, given the reliability and maintenance periods of modern superconducting linacs, may affect the microstructure evolution of test materials and needs evaluation.
- Advantages and disadvantages of liquid and solid targets were discussed and found that either technology could be made to work; the optimal choice depending upon the final design requirements.
- There was general consensus that combining the particle physics mission with the nuclear energy mission into a single target station would be preferable to separate target stations competing for proton beam current (assuming each mission receives approximately half of the available current).
- Specific actions to further evolve the concept of an Energy Station were identified and are listed under Future Considerations.

8.0 Additional Resources

Project X Workshop Website: https://indico.fnal.gov/conferenceDisplay.py?ovw=True&confId=5836)

Workshop Charge: https://indico.fnal.gov/getFile.py/access?resId=3&materialId=0&confId=5836

Workshop Agenda: https://indico.fnal.gov/materialDisplay.py?materialId=paper&confId=5836

List of Attendees: http://www-ppd.fnal.gov/conf-w/PXES13/Part.PDF

Presentations: https://indico.fnal.gov/conferenceTimeTable.py?confId=5836#20130129.detailed (Select the presenter for each day to access the presentation.)

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